Test of Lorentz and CPT violation with neutrinos

Outline

1. Why Lorentz violation is interesting with short baseline neutirno oscillations?
2. Test of Lorentz violation with neutrino oscillations
3. Lorentz violation with LSND
4. Lorentz violation with MiniBooNE neutrino data
5. Lorentz violation with MiniBooNE anti-neutrino data
6. Conclusion

Teppei Katori for MiniBooNE collaboration
Massachusetts Institute of Technology
Short baseline neutrino workshop, Fermilab, Batavia, IL, May 13, 2011

1. Why Lorentz violation is interesting with short baseline neutrino oscillations?

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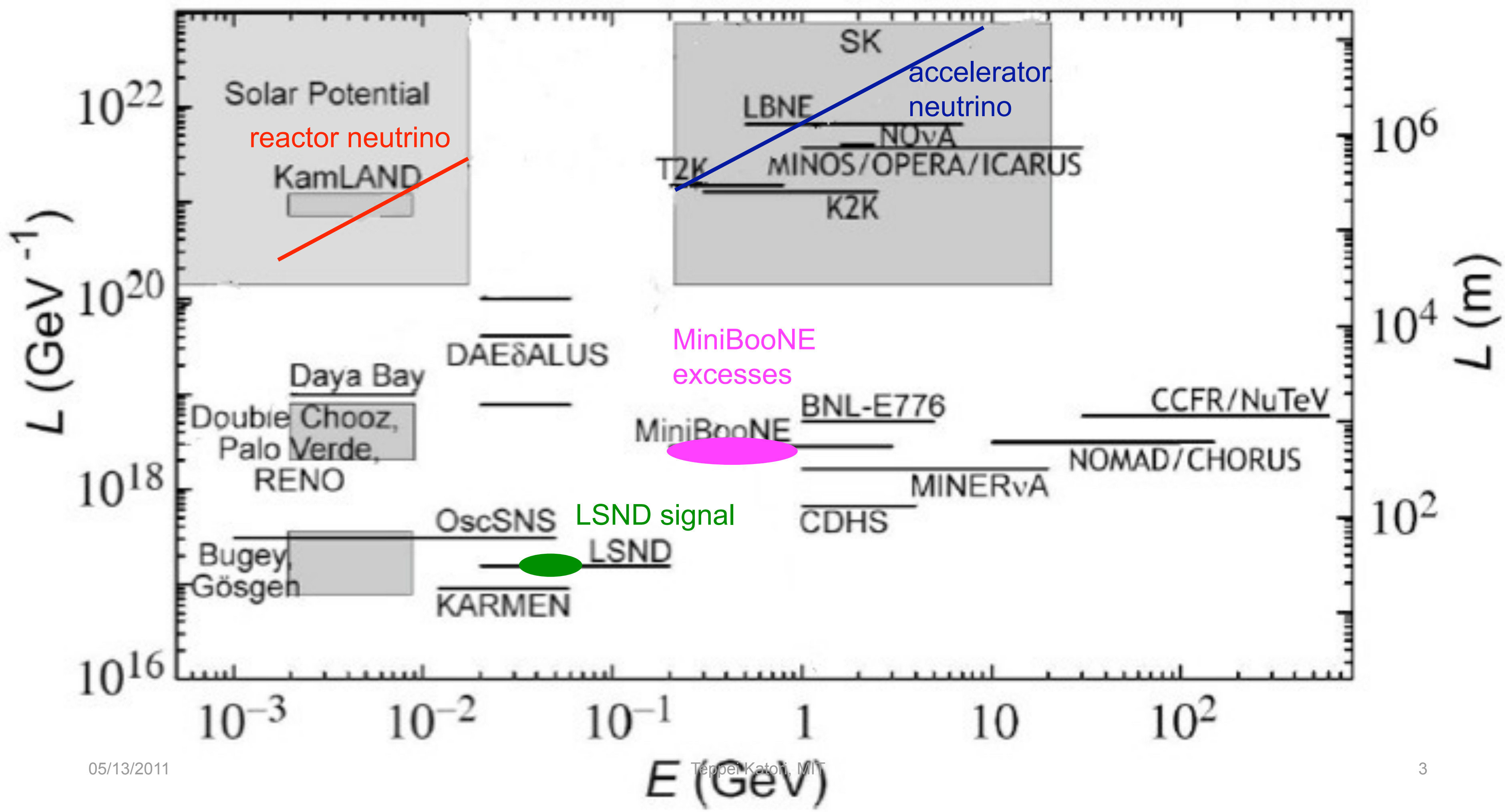
Diaz and Kostelecký
ArXiv:1012.5985

1. Why Lorentz violation is interesting in short baseline neutrino oscillations?

Model independent neutrino oscillation data is the function of neutrino energy and baseline
- Addition of Lorentz violation offers rich energy dependence on oscillation length



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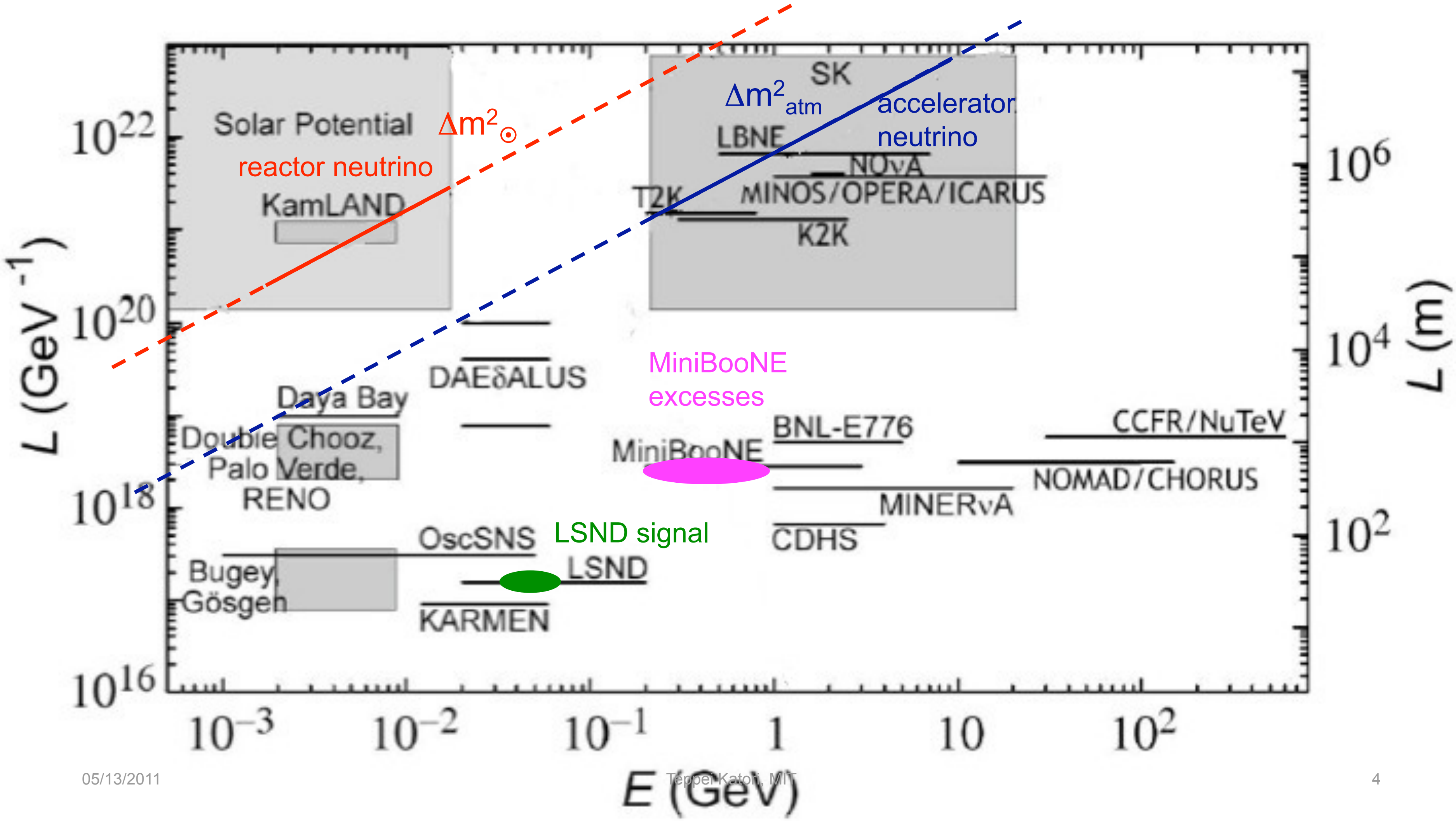

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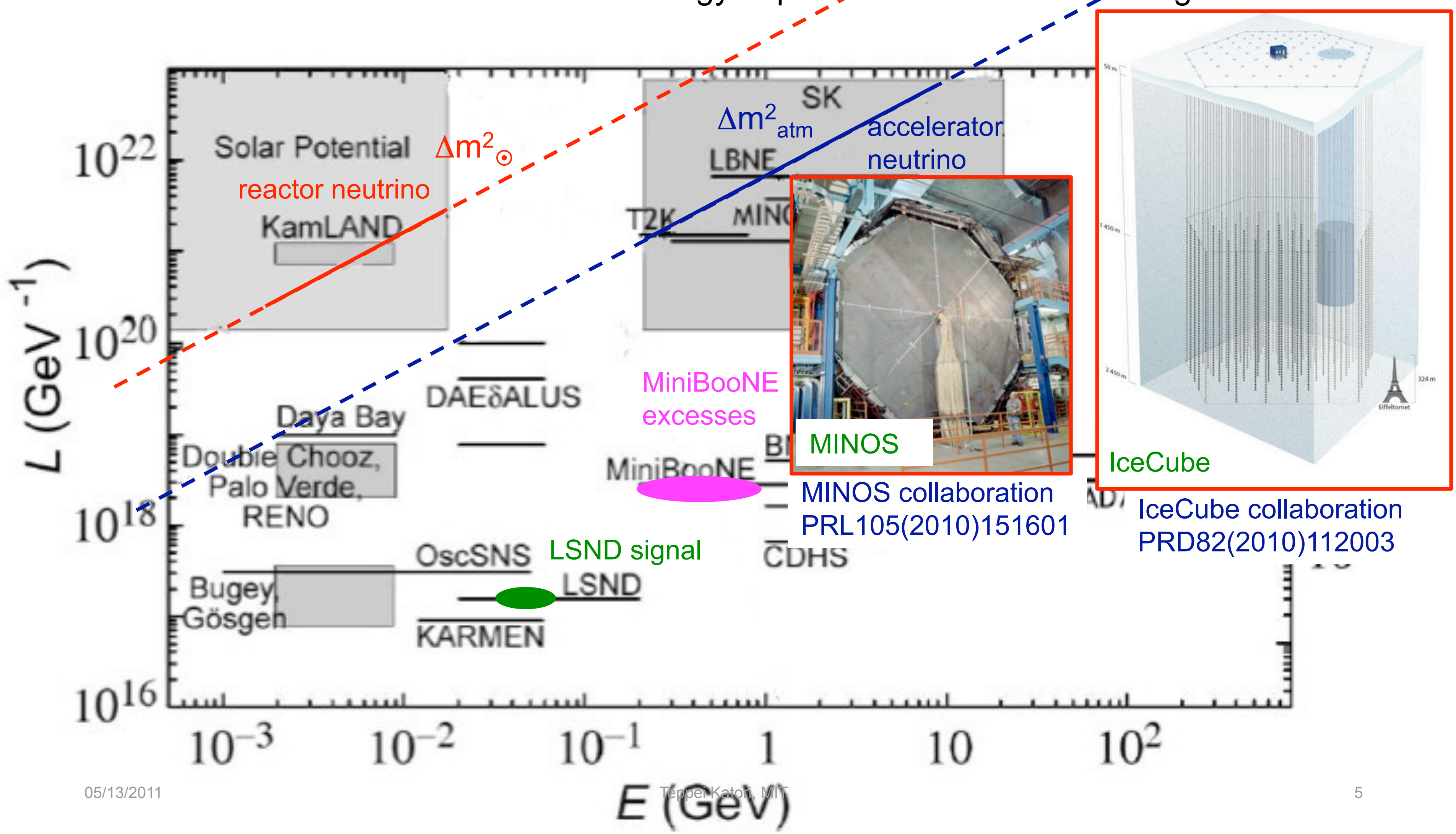

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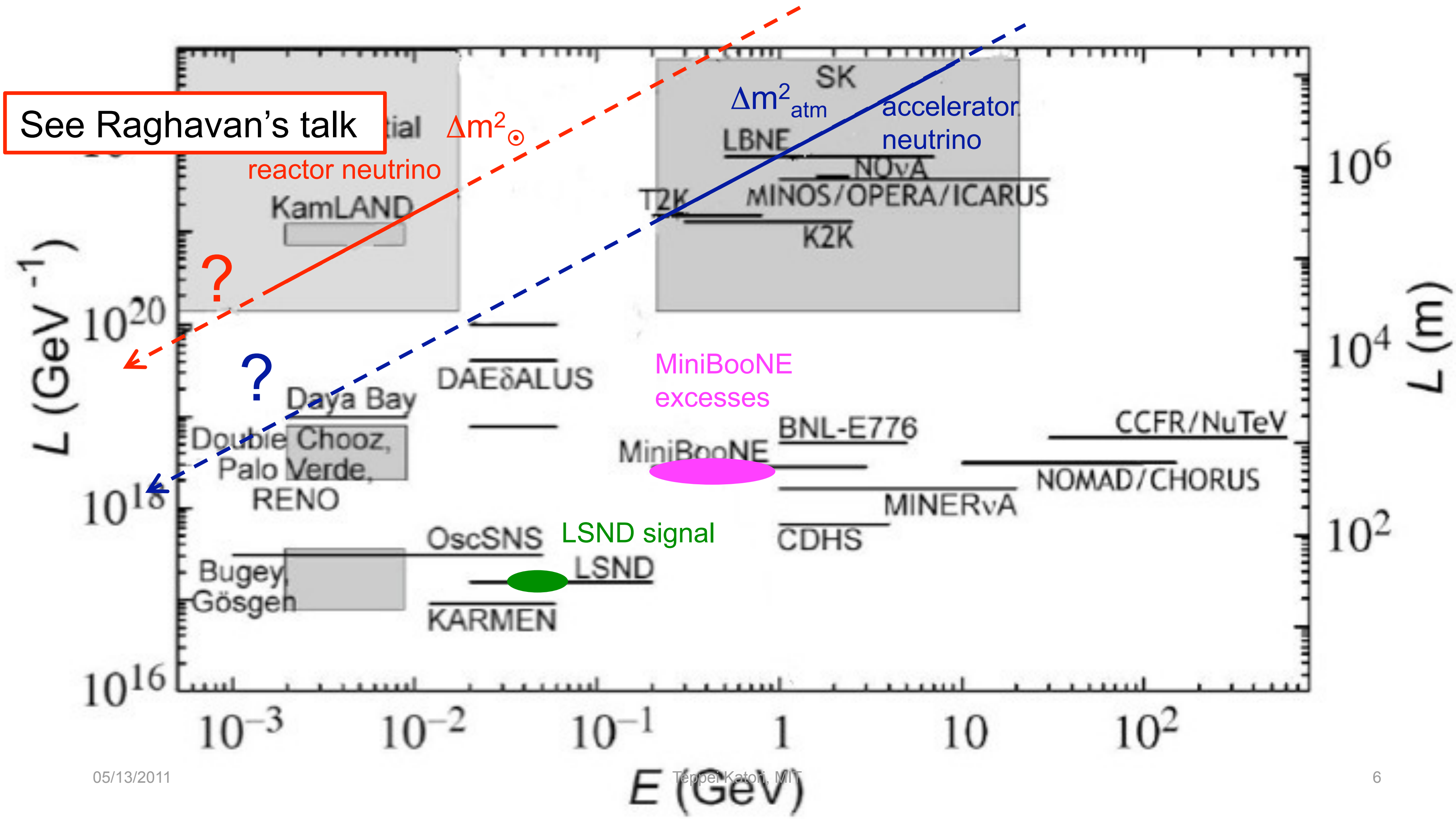

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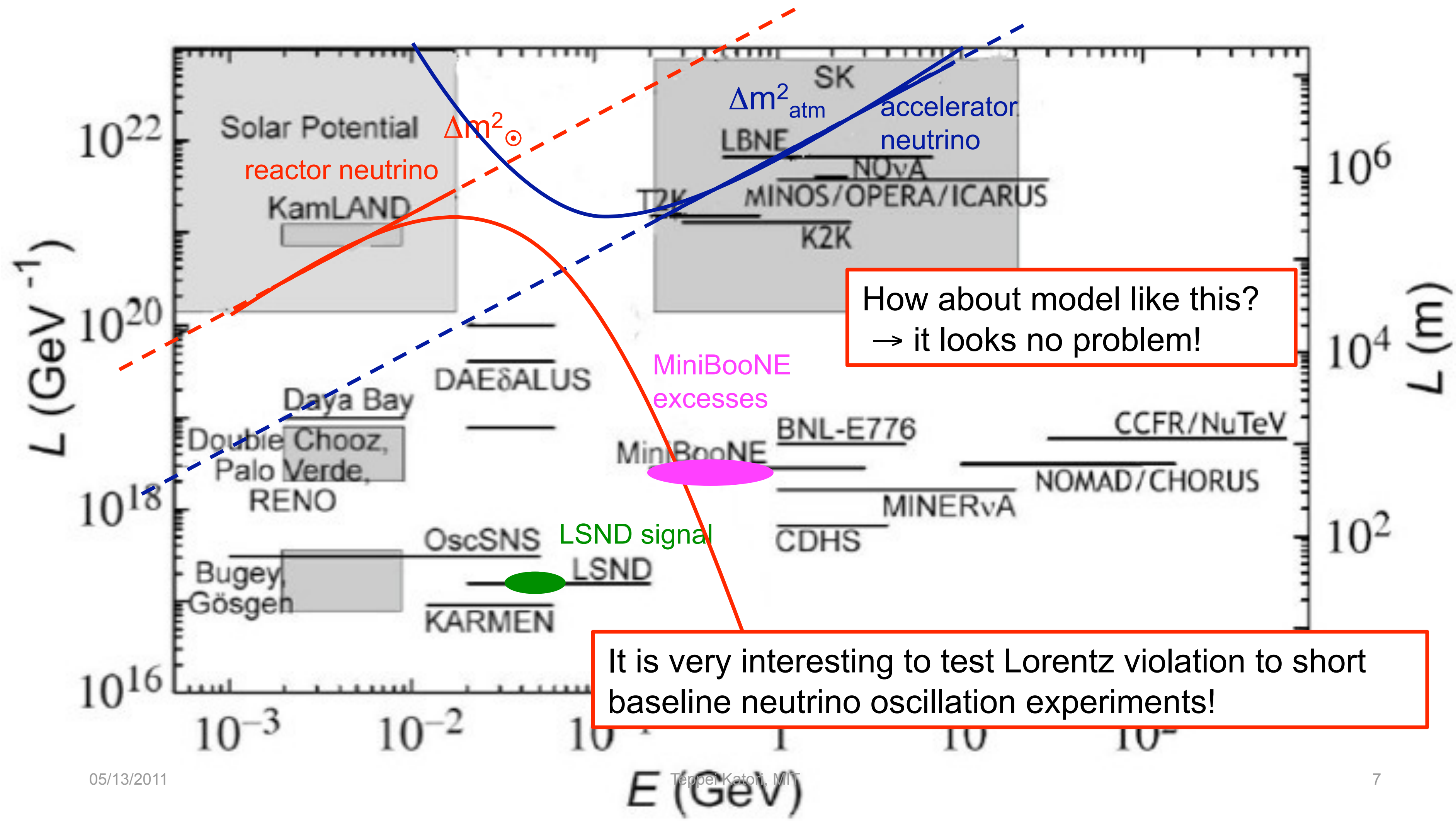


How about model like this?
→ it looks no problem!

It is very interesting to test Lorentz violation to short baseline neutrino oscillation experiments!

1. Why Lorentz violation is interesting with short baseline neutrino oscillations?

2. Test of Lorentz violation with neutrino oscillations

3. Lorentz violation with LSND

4. Lorentz violation with MiniBooNE neutrino data

5. Lorentz violation with MiniBooNE anti-neutrino data

6. Conclusion

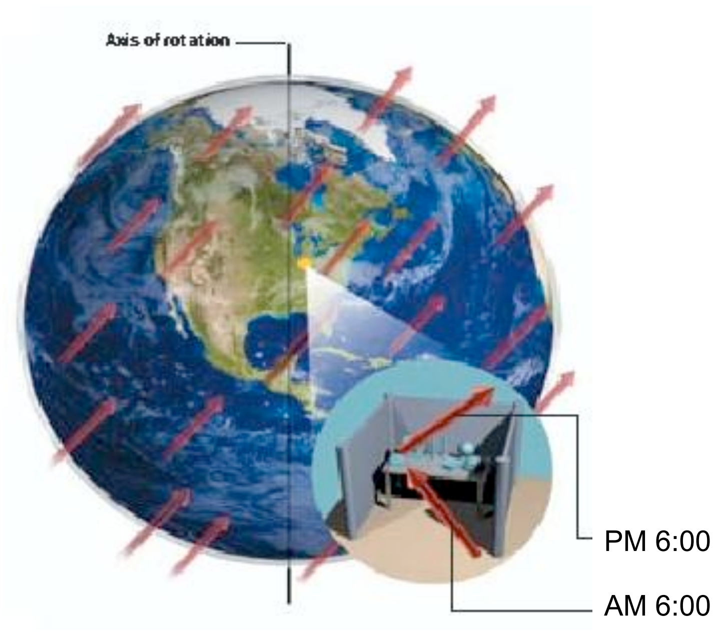
2. Test of Lorentz violation with neutrino oscillations

How to detect Lorentz violation?

Lorentz violation is realized as a coupling of particle fields and the background fields, so the basic strategy is to find the Lorentz violation is;

(1) choose the coordinate system to compare the experimental result
(2) write down Lagrangian including Lorentz violating terms under the formalism
(3) write down the observables using this Lagrangian

Scientific American (Sept. 2004)



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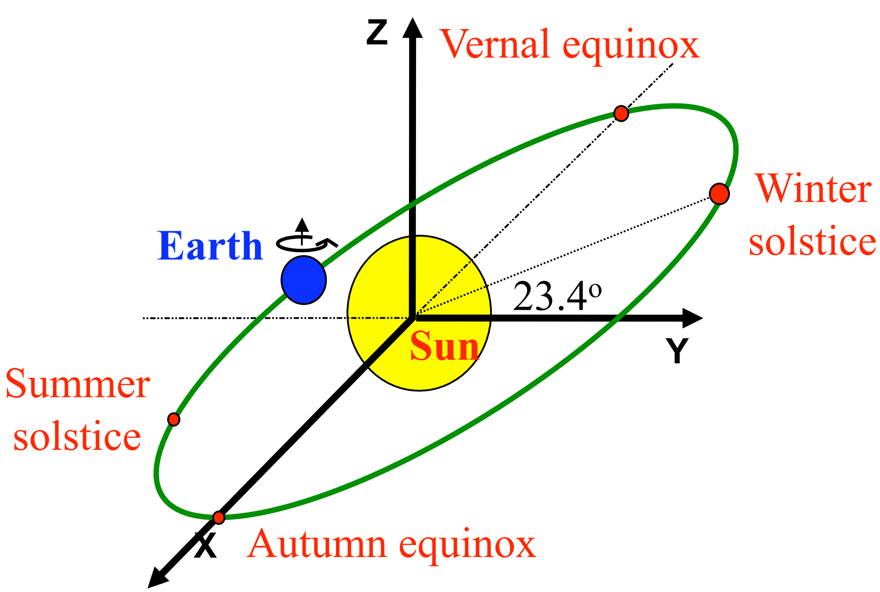
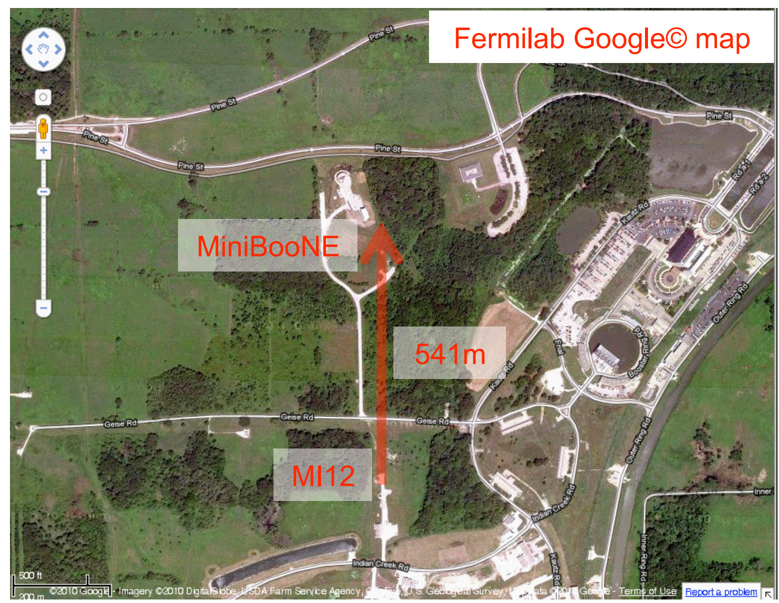
The standard choice of the coordinate is Sun-centred celestial equatorial coordinates





Colladay and Kostelecký
PRD55(1997)6760

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As a standard formalism for the general search of Lorentz violation, Standard Model Extension (SME) is widely used in the community. SME is self-consistent low-energy effective theory with Lorentz and CPT violation within conventional QM (minimum extension of QFT with Particle Lorentz violation)

Modified Dirac Equation (MDE) for neutrinos

$$i(\Gamma^{\nu}_{AB}\partial_{\nu} - M_{AB})\nu_{B} = 0$$

SME parameters

$$\Gamma^{\nu}_{AB} = \gamma^{\nu}\delta_{AB} + c^{\mu\nu}_{AB}\gamma_{\mu} + d^{\mu\nu}_{AB}\gamma_{\mu}\gamma_{5} + e^{\nu}_{AB} + if^{\nu}_{AB}\gamma_{5} + \frac{1}{2}g^{\lambda\mu\nu}_{AB}\sigma_{\lambda\mu}$$

$$M_{AB} = m_{AB} + im_{5AB}\gamma_{5} + a^{\mu}_{AB}\gamma_{\mu} + b^{\mu}_{AB}\gamma_{5}\gamma_{\mu} + \frac{1}{2}H^{\mu\nu}_{AB}\sigma_{\mu\nu}$$

$c^{\mu\nu}_{AB}$ ← 4X4 Lorentz indices ← 6X6 flavor indices

Lorentz and CPT violating term
$a^{\mu}, b^{\mu}, e^{\mu}, f^{\mu}, g^{\mu\nu\lambda}$

Lorentz violating term
$c^{\mu\nu}, d^{\mu\nu}, H^{\mu\nu}$

Kostelecký and Mewes
PRD69(2004)076002

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How to detect Lorentz violation?

Lorentz violation is realized as a coupling of particle fields and the background fields, so the basic strategy is to find the Lorentz violation is;

(1) choose the coordinate system to compare the experimental result
(2) write down Lagrangian including Lorentz violating terms under the formalism
(3) write down the observables using this Lagrangian

The observables can be, energy spectrum, frequency of atomic transition, neutrino oscillation probability, etc. Among the non standard phenomena predicted by Lorentz violation, the smoking gun is the sidereal time dependence of the observables.

ex) Sidereal variation of MiniBooNE signal

$$P_{\nu_e \to \nu_\mu} \sim \frac{|(h_{eff})_{e\mu}|^2 L^2}{(\hbar c)^2}$$

$$= \left(\frac{L}{\hbar c}\right)^2 |(C)_{e\mu} + (A_s)_{e\mu} \sin w_\oplus T_\oplus + (A_c)_{e\mu} \cos w_\oplus T_\oplus + (B_s)_{e\mu} \sin 2w_\oplus T_\oplus + (B_c)_{e\mu} \cos 2w_\oplus T_\oplus|^2$$

sidereal frequency $w_\oplus = \dfrac{2\pi}{23\text{h}56\text{m}4.1\text{s}}$

sidereal time $T_\oplus$

Sidereal variation analysis for MiniBooNE is 5 parameter fitting problem

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4. Lorentz violation with MiniBooNE neutrino data

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LSND Collaboration,
PRD64(2001)112007

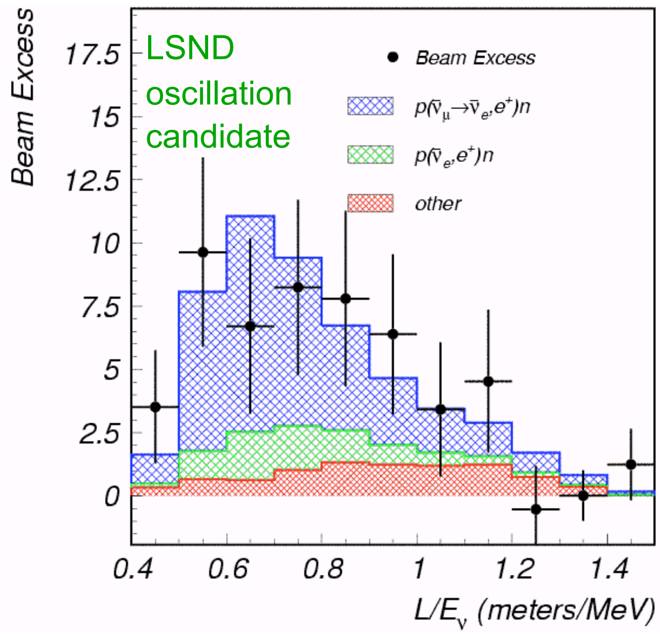
3. Lorentz violation with LSND

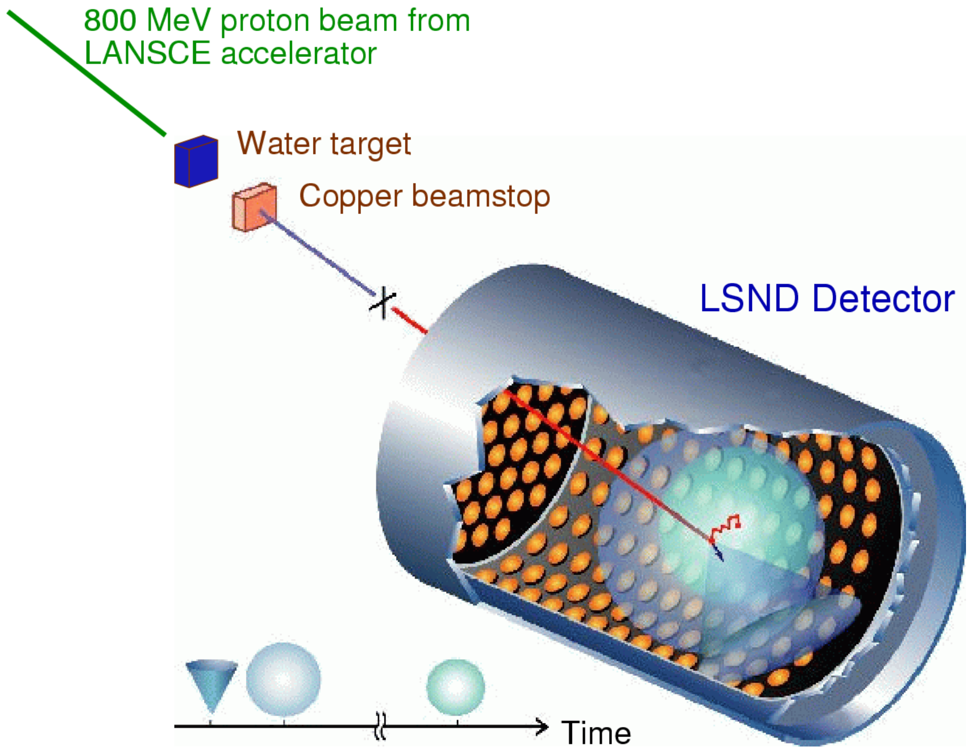
Neutrino mode low energy excess

LSND experiment at Los Alamos observed excess of anti-electron neutrino events in the anti-muon neutrino beam.

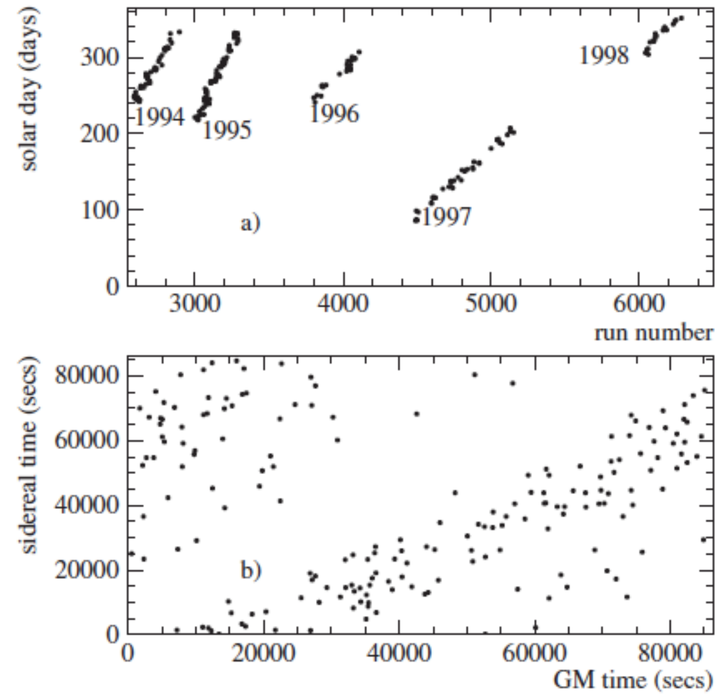
87.9 ± 22.4 ± 6.0 (3.8.σ)

This is not predicted by neutrino standard model (νSM), so it is interesting to test Lorentz violation with LSND data.





3. Lorentz violation with LSND



Data taking period
- if data taking is uniform with time, all day-night effect would be smeared out (not the case for LSND)

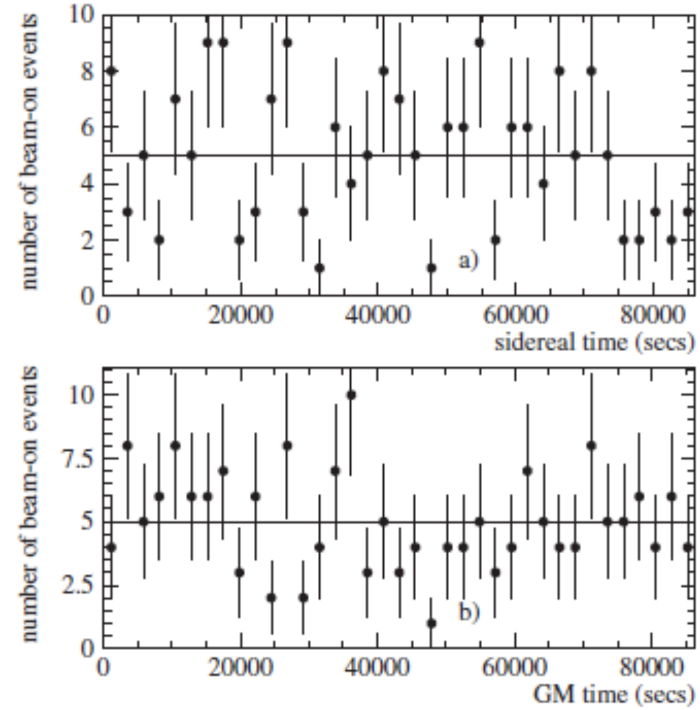
Solar time distribution
- to check day-night effect

Flatness test
- to test the consistency with no sidereal variation

Flat hypothesis (solar time)
P(K-S)=0.39

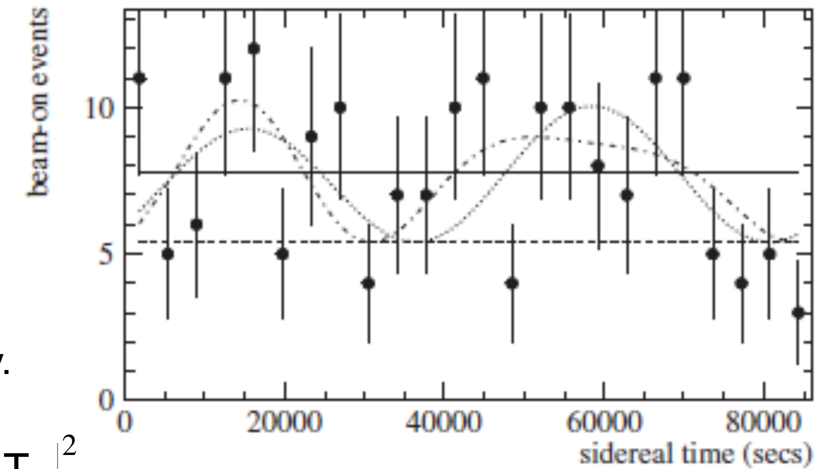
Flat hypothesis (sidereal time)
P(K-S)=0.23

Neutrino mode excess is compatible with flat hypothesis.



LSND Collaboration,
PRD72(2005)076004

3. Lorentz violation with LSND



Unbinned likelihood fit

- maximum statistics power for low statistics data (186 events).

3 parameter fit result

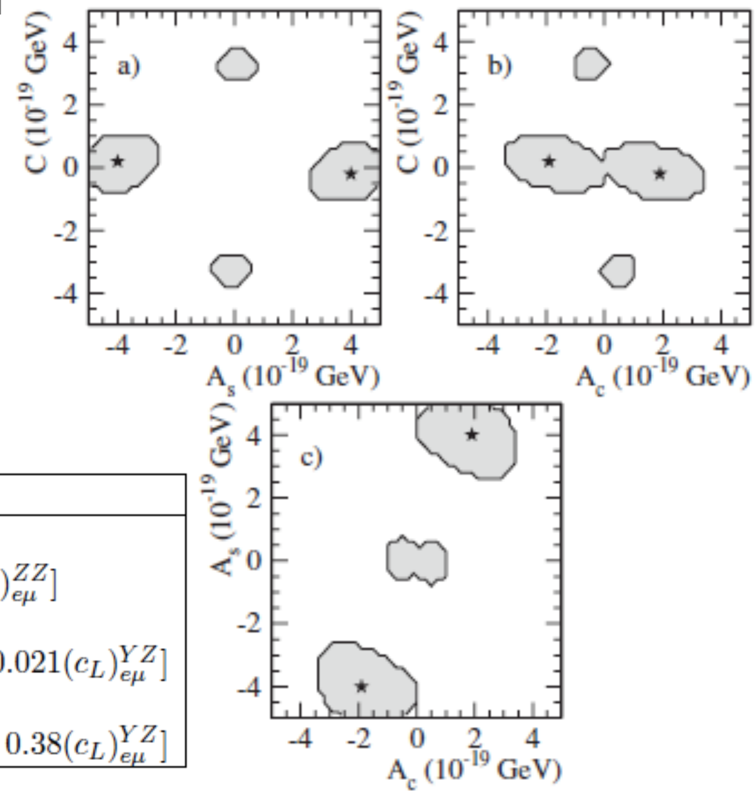
- statistics doesn't allow to fit 5 parameters simultaneously.

$$P_{\bar{\nu}_e \to \bar{\nu}_\mu} = \left(\frac{L}{\hbar c}\right)^2 \left| (C)_{\bar{e}\bar{\mu}} + (A_s)_{\bar{e}\bar{\mu}} \sin w_\oplus T_\oplus + (A_c)_{\bar{e}\bar{\mu}} \cos w_\oplus T_\oplus \right|^2$$

- because of the nature of the formula, solution is duplicated.

2 distinct solutions in 1-σ region (unit 10^{-19} GeV)

- solution 1: this solution include maximum loglikelihood (MLL) point, and sidereal time dependent solution.
- solution 2: this solution doesn't include MLL point, and sidereal time independent solution.



	soln1	$\delta 1$	soln2	SME parameter
$(\mathcal{C})_{e\mu}$	∓ 0.2	1.0	± 3.3	$\frac{(\tilde{m}^2)_{e\mu}}{2E} + (a_L)^T_{e\mu} + 0.19(a_L)^Z_{e\mu}$ $+E[-1.48(c_L)^{TT}_{e\mu} - 0.39(c_L)^{TZ}_{e\mu} + 0.44(c_L)^{ZZ}_{e\mu}]$
$(\mathcal{A}_s)_{e\mu}$	± 4.0	1.4	± 0.1	$0.98(a_L)^X_{e\mu} + 0.053(a_L)^Y_{e\mu}$ $+E[-1.96(c_L)^{TX}_{e\mu} - 0.11(c_L)^{TY}_{e\mu} - 0.38(c_L)^{XZ}_{e\mu} - 0.021(c_L)^{YZ}_{e\mu}]$
$(\mathcal{A}_c)_{e\mu}$	± 1.9	1.8	∓ 0.5	$0.053(a_L)^X_{e\mu} - 0.98(a_L)^Y_{e\mu}$ $+E[-0.11(c_L)^{TX}_{e\mu} + 1.96(c_L)^{TY}_{e\mu} - 0.021(c_L)^{XZ}_{e\mu} + 0.38(c_L)^{YZ}_{e\mu}]$

1. Why Lorentz violation is interesting with short baseline neutrino oscillations?

2. Test of Lorentz violation with neutrino oscillations

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4. **Lorentz violation with MiniBooNE neutrino data**

5. Lorentz violation with MiniBooNE anti-neutrino data

6. Conclusion

4. Lorentz violation with MiniBooNE neutrino data

MiniBooNE collaboration,
PRL102(2009)101802

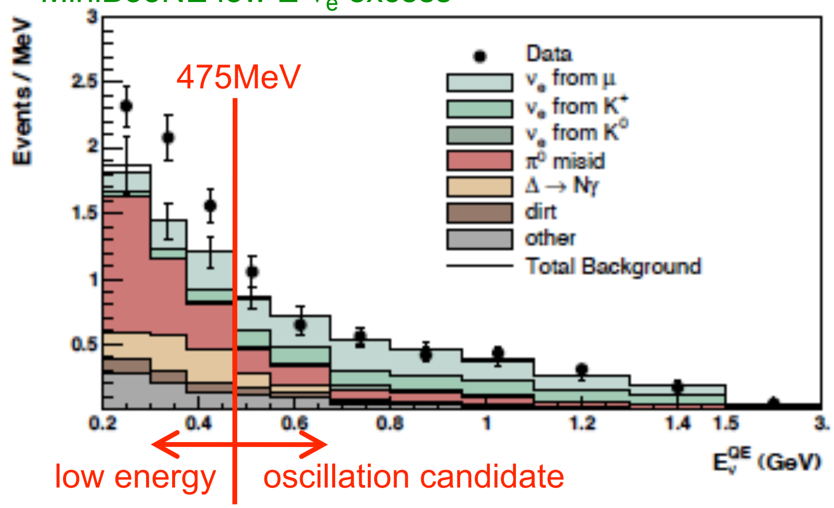
Neutrino mode low energy excess

MiniBooNE didn't see the signal at the region where LSND data suggested under the assumption of standard 2 massive neutrino oscillation model, but MiniBooNE did see the excess where neutrino standard model doesn't predict the signal.

The energy dependence of MiniBooNE is reproducible by Lorentz violation motivated model, such as Puma model (next talk).

The low energy excess may have sidereal time dependence.

MiniBooNE low E ν_e excess



All backgrounds are measured in other data sample and their errors are constrained

MiniBooNE collaboration,
PRL102(2009)101802

4. Lorentz violation with MiniBooNE neutrino data

Proton on target day-night variation

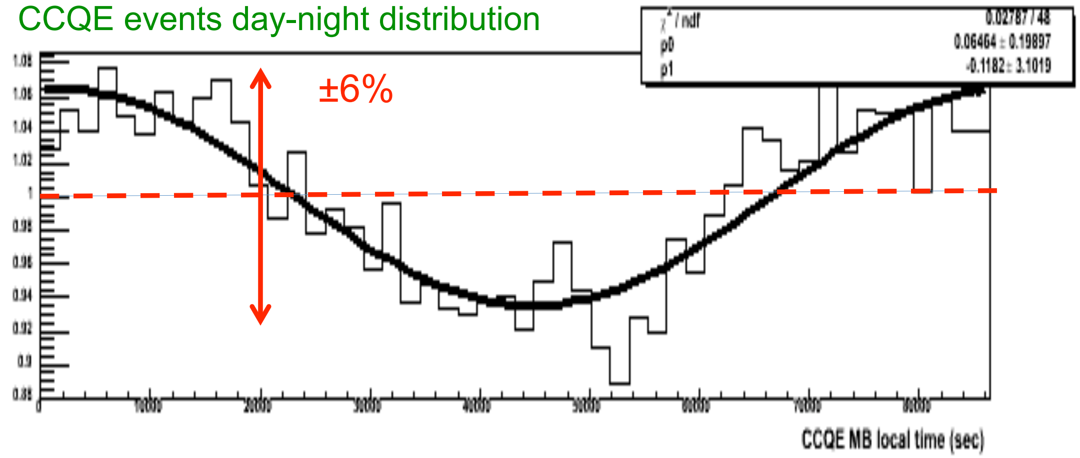
Since beam is running almost all year, any solar time structure, mainly POT day-night variation, is washed out in sidereal time.

Time dependent systematic errors are evaluated through observed CCQE events. The dominant source is POT variation.

POT makes 6% variation, but including this gives negligible effect in sidereal time distribution.

Therefore later we ignore all time dependent systematic errors.

CCQE events day-night distribution



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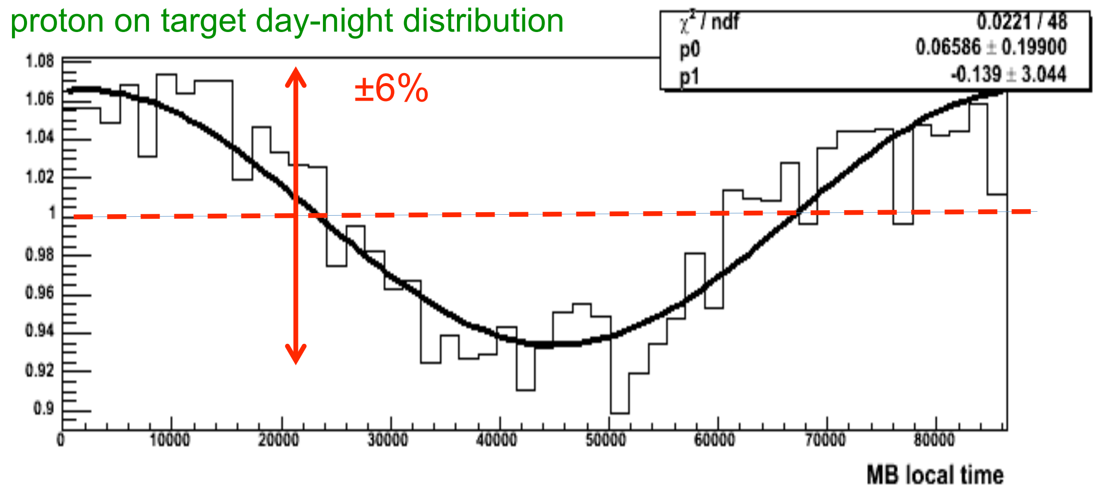


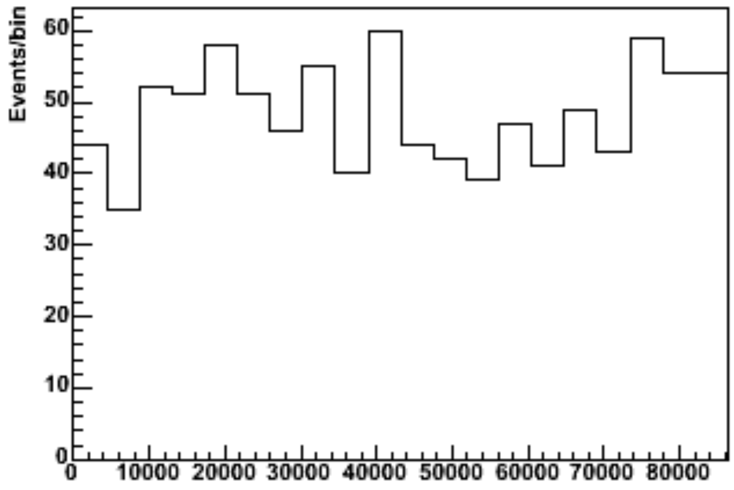
4. Lorentz violation with MiniBooNE neutrino data

Flatness test

The flatness hypothesis is tested in 2 ways, Pearson's χ^2 test (χ^2 test) and unbinned Kolmogorov-Smirnov test (K-S test).

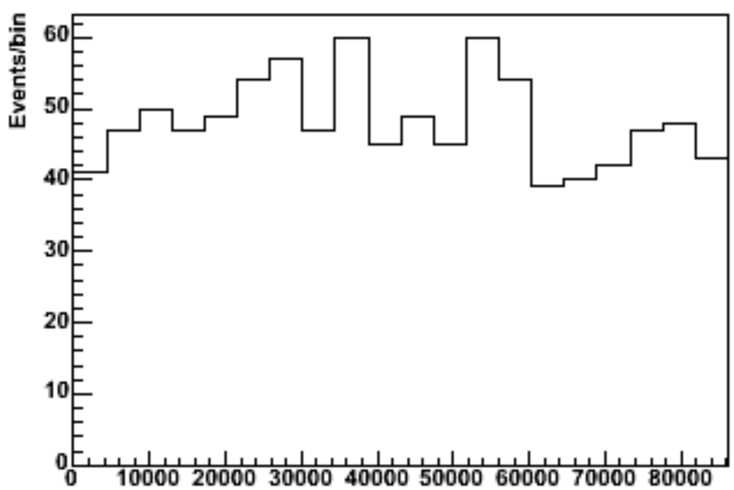
Flat hypothesis (solar time)
P(K-S)=0.64

Flat hypothesis (sidereal time)
P(K-S)=0.14



solar local time, 24h00m00s (86400s)

Neutrino mode excess is compatible with flat hypothesis.



sidereal time, 23h56m04s (86164s)

4. Lorentz violation with MiniBooNE neutrino data

Unbinned loglikelihood method

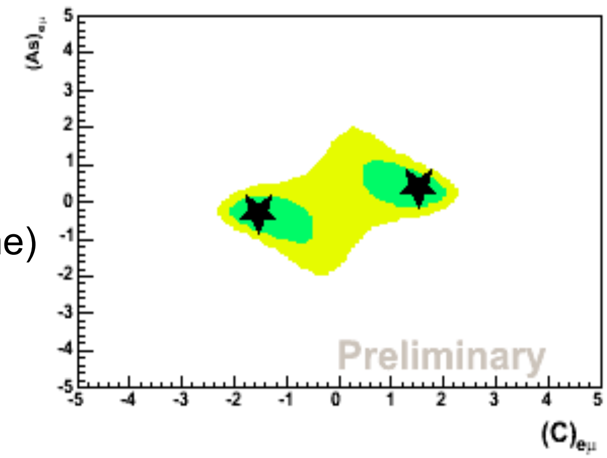
$$P_{\bar{\nu}_e \to \bar{\nu}_\mu} = \left(\frac{L}{\hbar c}\right)^2 \left|(C)_{\bar{e}\bar{\mu}} + (A_s)_{\bar{e}\bar{\mu}} \sin w_\oplus T_\oplus + (A_c)_{\bar{e}\bar{\mu}} \cos w_\oplus T_\oplus\right|^2$$

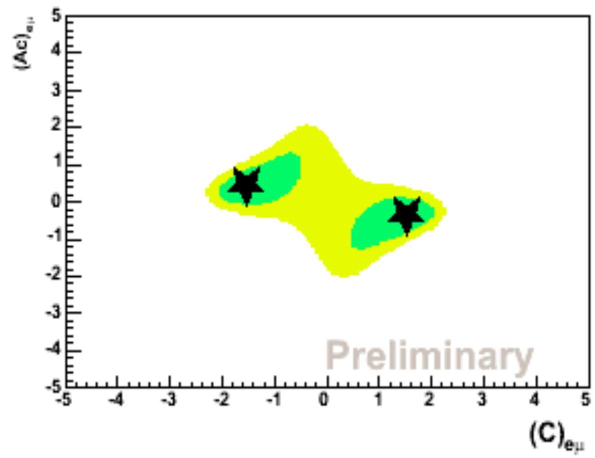
This method utilizes the highest statistical power

Flat hypothesis (solar time)
P(K-S)=0.64

Flat hypothesis (sidereal time)
P(K-S)=0.14

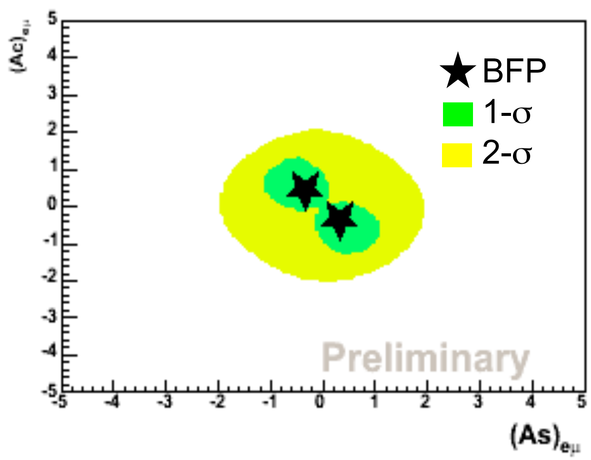
After fit (sidereal time)
P(K-S)=0.98

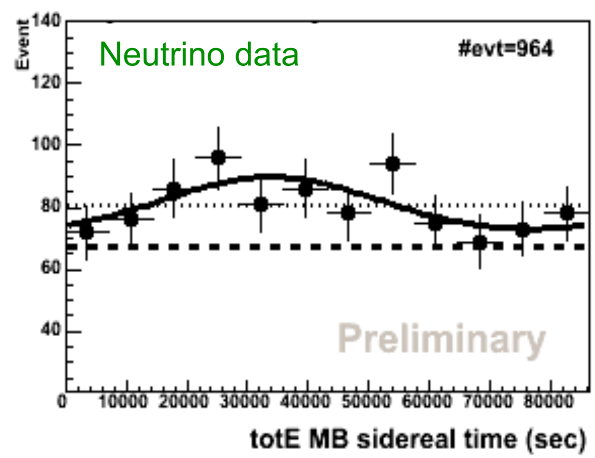




C-parameter is statistically significant value, but this is sidereal independent parameter.

Solution discovered by fit improve goodness-of-fit, but flat hypothesis is already a good solution.





4. Lorentz violation with MiniBooNE neutrino data

For neutrino mode, P(K-S)=14% before fit, so data is consistent with no sidereal variation hypothesis. After fit, P(K-S)=98%, however, the best fit point has strong signal on C-term (not sidereal time dependent)

Unbinned loglikelihood method

This method utilizes the highest statistical power

Flat hypothesis (solar time)
P(K-S)=0.64

Flat hypothesis (sidereal time)
P(K-S)=0.14

After fit (sidereal time)
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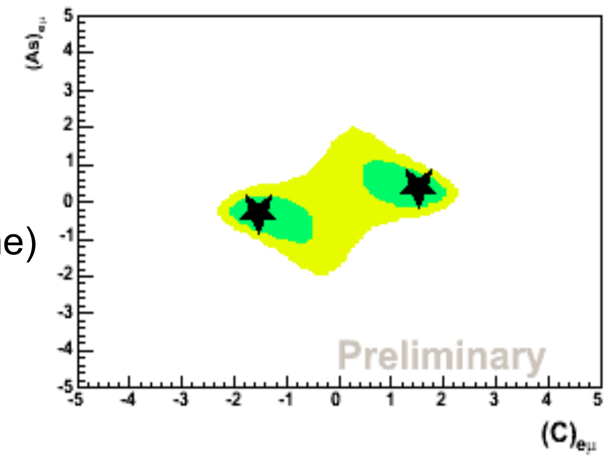

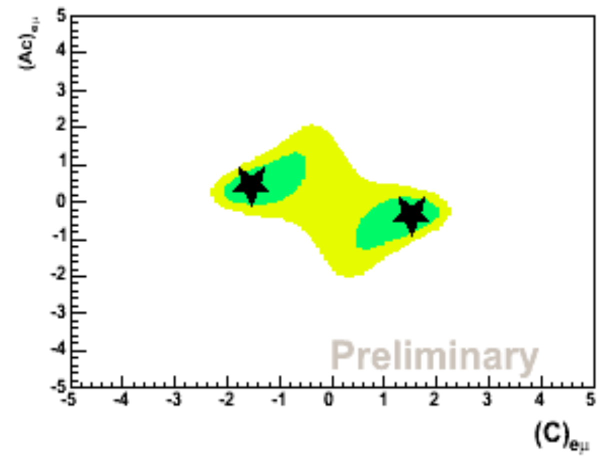

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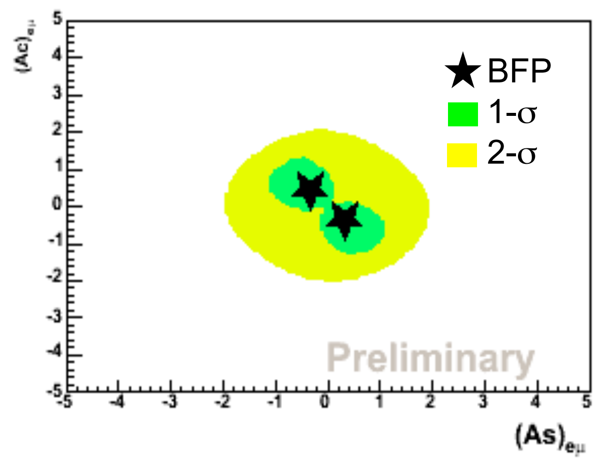

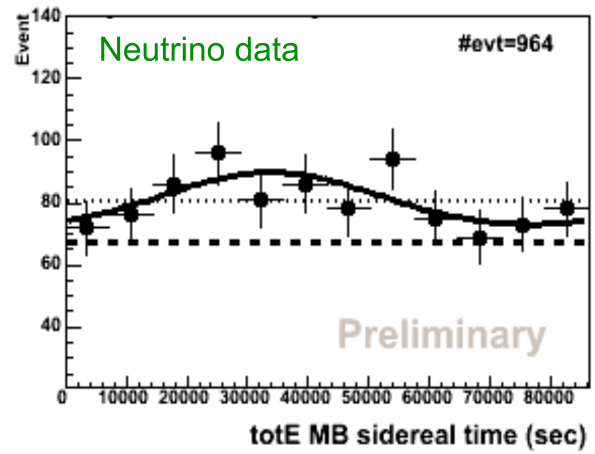

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MiniBooNE collaboration,
PRL105(2010)181801

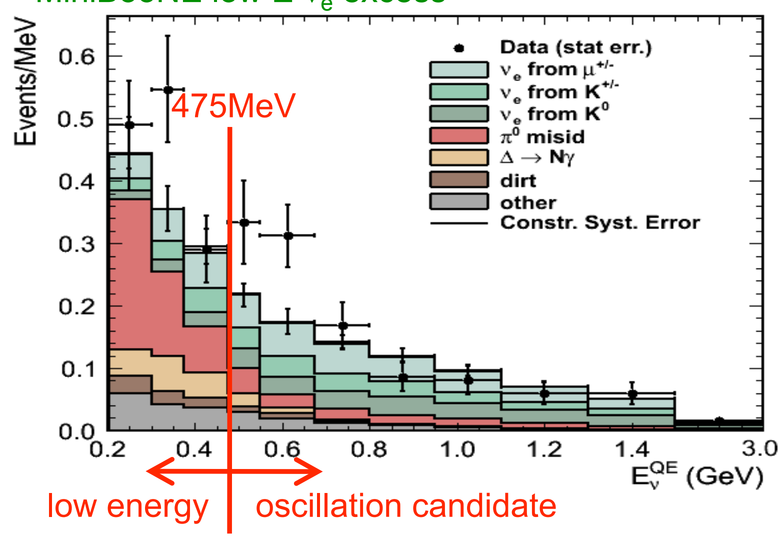
5. Lorentz violation with MiniBooNE anti-neutrino data

Anti-neutrino mode low energy excess

MiniBooNE did see the signal at the region where LSND data suggested under the assumption of standard two massive neutrino oscillation model.

If the excess were Lorentz violation, the excess may have sidereal time dependence.

MiniBooNE low E ν_e excess



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The flatness hypothesis is tested in 2 ways, Pearson's χ^2 test (χ^2 test) and unbinned Kolmogorov-Smirnov test (K-S test).

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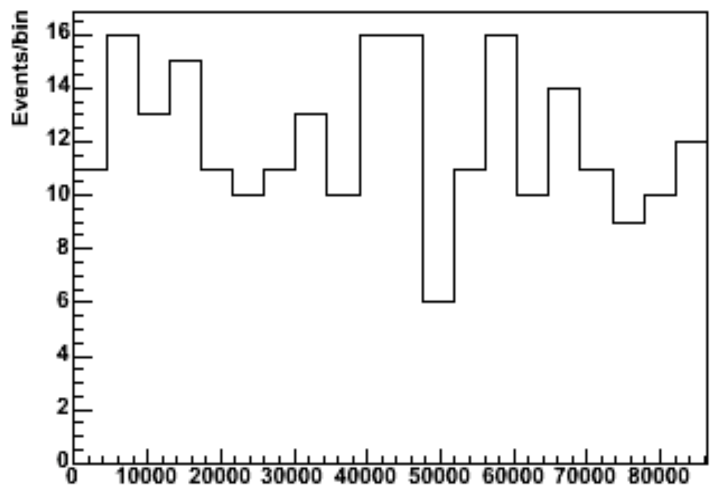
P(K-S)=0.69

Flat hypothesis (sidereal time)
P(K-S)=0.08



solar local time, 24h00m00s (86400s)

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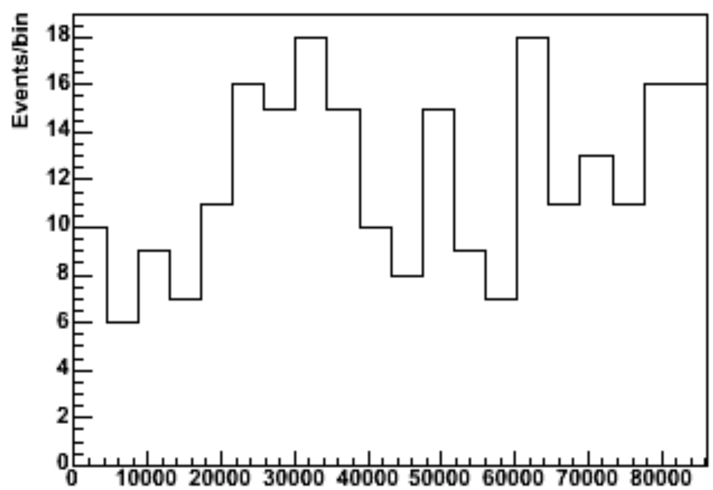

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Unbinned loglikelihood method

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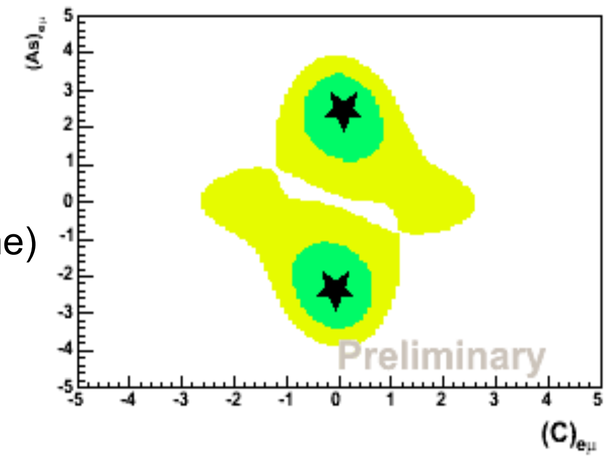
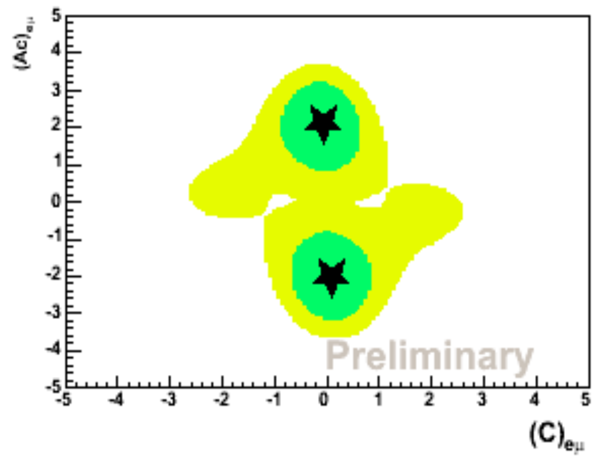
This method utilizes the highest statistical power

Flat hypothesis (solar time)
P(K-S)=0.69

Flat hypothesis (sidereal time)
P(K-S)=0.08

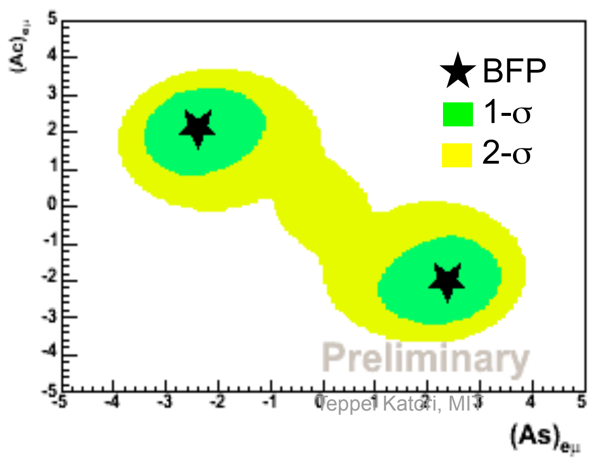
After fit (sidereal time)
P(K-S)=0.63

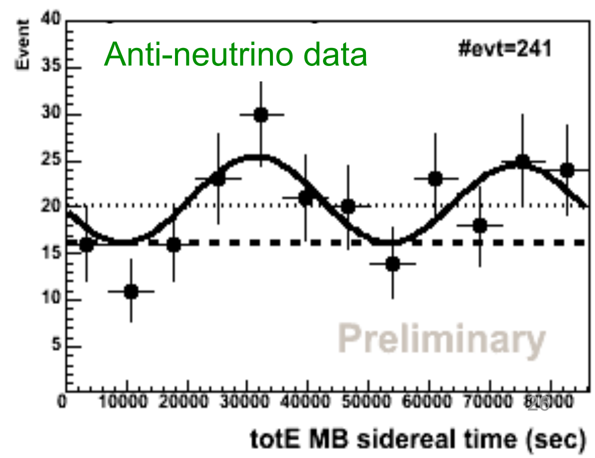




Large As- and Ac- terms are preferred within 1-σ (sidereal time dependent solution).

2-σ contour encloses large C-term (sidereal time independent solution).





5. Lorentz violation with MiniBooNE anti-neutrino data

For anti-neutrino mode, P(K-S)=8% before fit, so data is consistent with no sidereal variation hypothesis. After fit, P(K-S)=63%, also, the best fit point has signal on As- and Ac-term (sidereal time dependent)

Unbinned loglikelihood method

This method utilizes the highest statistical power

Flat hypothesis (solar time)
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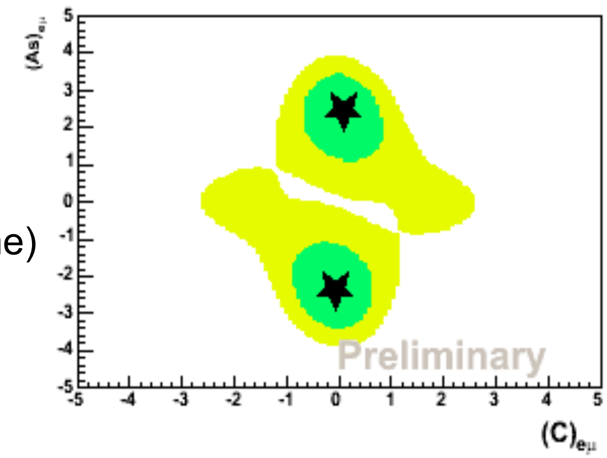
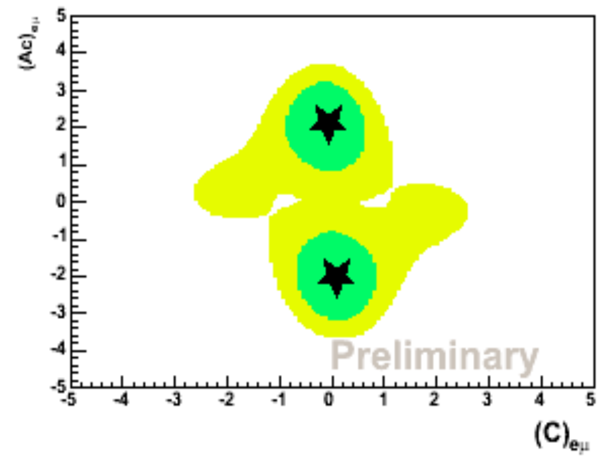
Flat hypothesis (sidereal time)
P(K-S)=0.08

After fit (sidereal time)
P(K-S)=0.63





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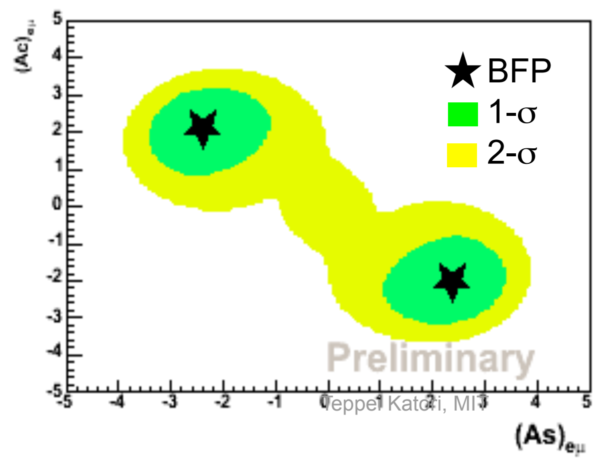
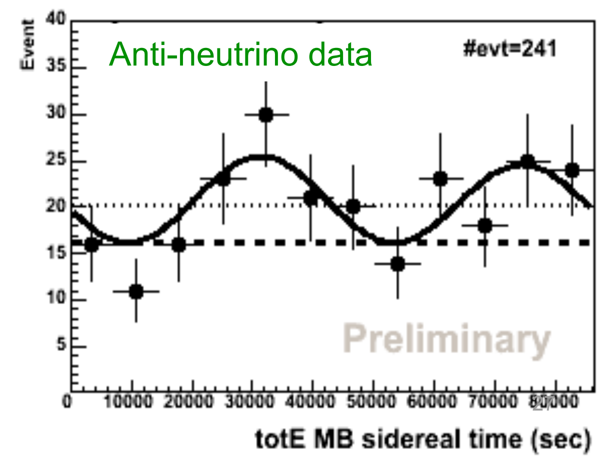
2-σ contour encloses large C-term (sidereal time independent solution).





5. Lorentz violation with MiniBooNE anti-neutrino data

For anti-neutrino mode, P(K-S)=8% before fit, so data is consistent with no sidereal variation hypothesis. After fit, P(K-S)=63%, also, the best fit point has signal on As- and Ac-term (sidereal time dependent)

Unbinned loglikelihood method

This method utilizes the highest statistical power

Flat hypothesis (solar time)
P(K-S)=0.69

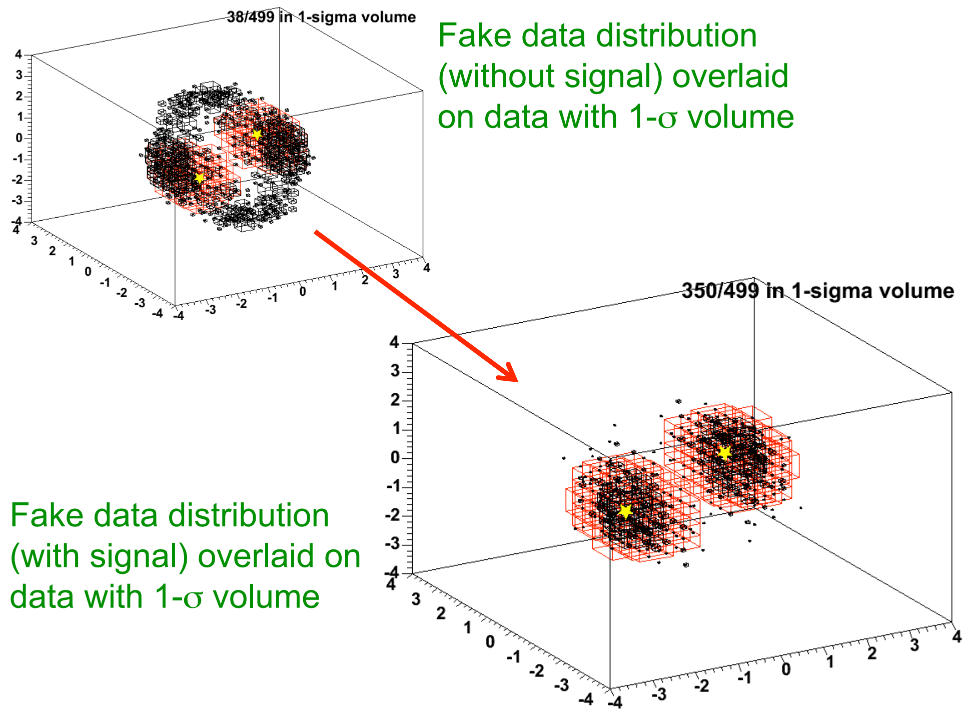
Flat hypothesis (sidereal time)
P(K-S)=0.08

After fit (sidereal time)
P(K-S)=0.63

Large As- and Ac- terms are preferred within 1-σ (sidereal time dependent solution).

2-σ contour encloses large C-term (sidereal time independent solution).

Fake data $\Delta\chi^2$ study says there is 3% chance this signal is by random fluctuation.



Fake data distribution (without signal) overlaid on data with 1-σ volume

Fake data distribution (with signal) overlaid on data with 1-σ volume

6. Conclusions

Lorentz and CPT violation has been shown to occur in Planck scale physics.

LSND and MiniBooNE data suggest Lorentz violation is an interesting solution of neutrino oscillation.

MiniBooNE neutrino mode summary
P(K-S)=14% before fit, so data is consistent with no sidereal variation hypothesis. After fit, P(K-S)=98%, however, the best fit point has strong signal on C-term (not sidereal time dependent).

MiniBooNE anti-neutrino mode summary
P(K-S)=8% before fit, so data is consistent with no sidereal variation hypothesis. After fit, P(K-S)=63%, also, the best fit point has strong signal on As- and Ac-term (sidereal time dependent).

Extraction of SME coefficients is undergoing.

BooNE collaboration

University of Alabama
Bucknell University
University of Cincinnati
University of Colorado
Columbia University
Embry Riddle Aeronautical University
Fermi National Accelerator Laboratory
Indiana University
University of Florida

Los Alamos National Laboratory
Louisiana State University
Massachusetts Institute of Technology
University of Michigan
Princeton University
Saint Mary's University of Minnesota
Virginia Polytechnic Institute
Yale University

Thank you for your attention!

Backup

Kostelecký and Mewes
PRD69(2004)076002

2. Test of Lorentz violation with neutrino oscillations

Sidereal variation of neutrino oscillation probability for MiniBooNE (5 parameters)

$$P_{\bar{\nu}_e\to\bar{\nu}_\mu} = \left(\frac{L}{\hbar c}\right)^2 \left|(C)_{\bar{e}\bar{\mu}} + (A_s)_{\bar{e}\bar{\mu}} \sin w_\oplus T_\oplus + (A_c)_{\bar{e}\bar{\mu}} \cos w_\oplus T_\oplus + (B_s)_{\bar{e}\bar{\mu}} \sin 2w_\oplus T_\oplus + (B_c)_{\bar{e}\bar{\mu}} \cos 2w_\oplus T_\oplus\right|^2$$

Expression of 5 observables (14 SME parameters)

$$(C)_{\bar{e}\bar{\mu}} = (a_L)^T_{\bar{e}\bar{\mu}} - N^Z(a_L)^Z_{\bar{e}\bar{\mu}} + E\left[-\frac{1}{2}(3-N^ZN^Z)(c_L)^{TT}_{\bar{e}\bar{\mu}} + 2N^Z(c_L)^{TZ}_{\bar{e}\bar{\mu}} + \frac{1}{2}(1-3N^ZN^Z)(c_L)^{ZZ}_{\bar{e}\bar{\mu}}\right]$$

$$(A_s)_{\bar{e}\bar{\mu}} = N^Y(a_L)^X_{\bar{e}\bar{\mu}} - N^X(a_L)^Y_{\bar{e}\bar{\mu}} + E\left[-2N^Y(c_L)^{TX}_{\bar{e}\bar{\mu}} + 2N^X(c_L)^{TY}_{\bar{e}\bar{\mu}} + 2N^YN^Z(c_L)^{XZ}_{\bar{e}\bar{\mu}} - 2N^XN^Z(c_L)^{YZ}_{\bar{e}\bar{\mu}}\right]$$

$$(A_c)_{\bar{e}\bar{\mu}} = -N^X(a_L)^X_{\bar{e}\bar{\mu}} - N^Y(a_L)^Y_{\bar{e}\bar{\mu}} + E\left[2N^X(c_L)^{TX}_{\bar{e}\bar{\mu}} + 2N^Y(c_L)^{TY}_{\bar{e}\bar{\mu}} - 2N^XN^Z(c_L)^{XZ}_{\bar{e}\bar{\mu}} - 2N^YN^Z(c_L)^{YZ}_{\bar{e}\bar{\mu}}\right]$$

$$(B_s)_{\bar{e}\bar{\mu}} = E\left[N^XN^Y\left((c_L)^{XX}_{\bar{e}\bar{\mu}} - (c_L)^{YY}_{\bar{e}\bar{\mu}}\right) - (N^XN^X - N^YN^Y)(c_L)^{XY}_{\bar{e}\bar{\mu}}\right]$$

$$(B_c)_{\bar{e}\bar{\mu}} = E\left[-\frac{1}{2}(N^XN^X - N^YN^Y)\left((c_L)^{XX}_{\bar{e}\bar{\mu}} - (c_L)^{YY}_{\bar{e}\bar{\mu}}\right) - 2N^XN^Y(c_L)^{XY}_{\bar{e}\bar{\mu}}\right]$$

$$\begin{pmatrix} N^X \\ N^Y \\ N^Z \end{pmatrix} = \begin{pmatrix} \cos\chi\sin\theta\cos\phi - \sin\chi\cos\theta \\ \sin\theta\sin\phi \\ -\sin\chi\sin\theta\cos\phi - \cos\chi\cos\theta \end{pmatrix}$$

coordinate dependent direction vector
(depends on the latitude of FNAL, location of BNB and MiniBooNE detector)

5. Lorentz violation with MiniBooNE neutrino data

Unbinned extended maximum likelihood fit

- It has the maximum statistic power
- Assuming low energy excess is Lorentz violation, extract Lorentz violation parameters (SME parameters) from unbinned likelihood fit.

likelihood function

$$\Lambda = \frac{e^{-(\mu_s+\mu_b^v)}}{N!}\prod_{i=1}^{N}(\mu_s\mathcal{F}_s^i+\mu_b^v\mathcal{F}_b^i)\times\frac{1}{\sqrt{2\pi{\sigma_b}^2}}\exp\left(-\frac{(\mu_b^v-\mu_b)^2}{2{\sigma_b}^2}\right) \qquad (22)$$

N total number of event

μ_s predicted signal event number, function of fitting parameters

μ_b predicted background event number

$\mathcal{F}_s$ probability distribution of signal, function of sidereal time and fitting parameters

$\mathcal{F}_b$ probability distribution of background, not function of sidereal time

σ_b the $1-\sigma$ error of predicted the background

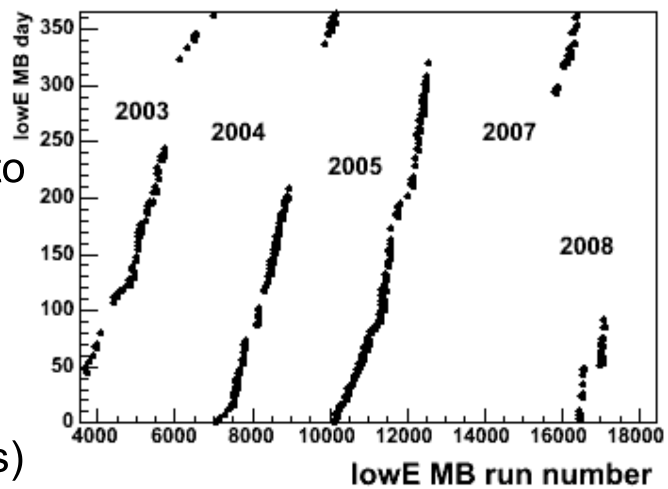
μ_b^v floating background event number floating within $1-\sigma$

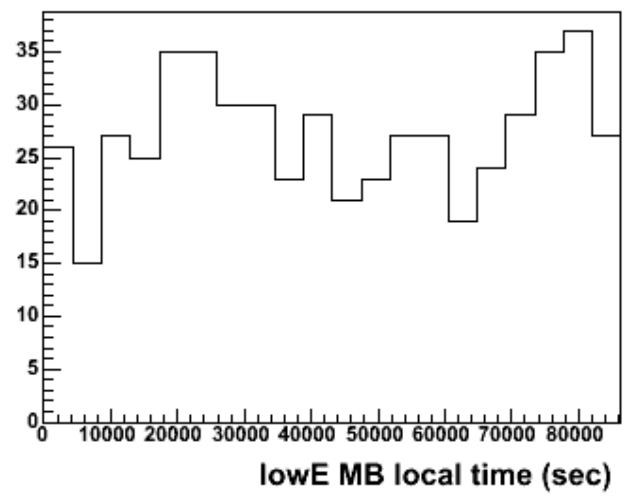
5. Lorentz violation with MiniBooNE neutrino data

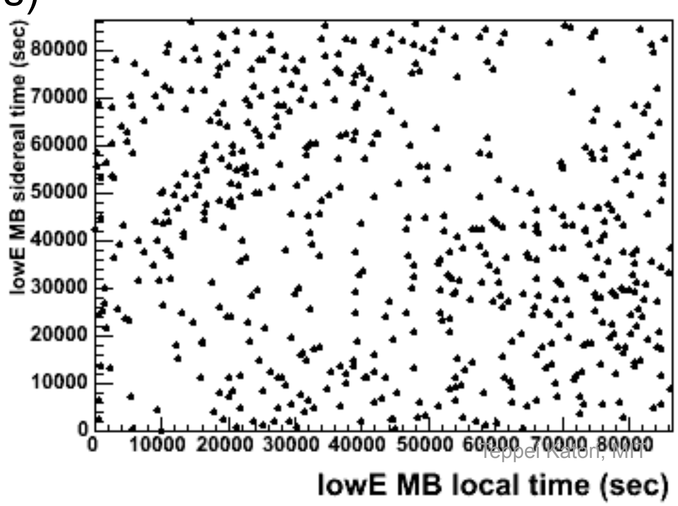
Time distribution of MiniBooNE neutrino mode low energy region

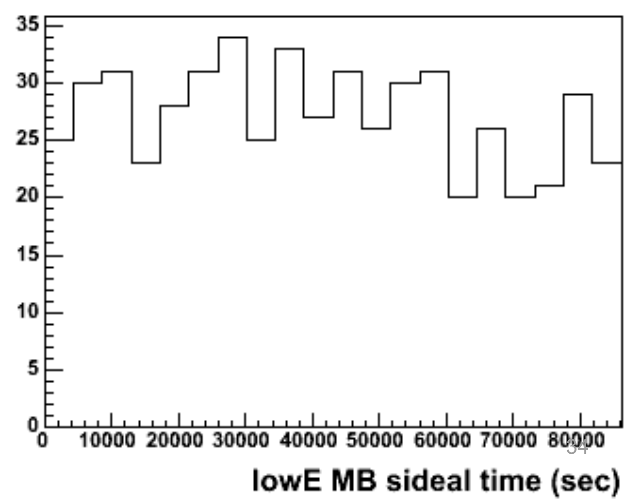
MiniBooNE data taking is reasonably uniform, so all day-night effect is likely to be washed out in sidereal time distribution.

solar local time 24h00m00s (86400s)
sidereal time 23h56m04s (86164s)









5. Lorentz violation with MiniBooNE neutrino data

Null hypothesis test

The flatness hypothesis is tested in 2 ways, Pearson's $\chi 2$ test ($\chi 2$ test) and unbinned Kolmogorov-Smirnov test (K-S test). K-S test has 3 advantages;

1. unbinned, so it has the maximum statistical power
2. no argument with bin choice
3. sensitive with sign change, called "run"

Non of tests shows any statistically significant results.
All data sets are compatible with flat hypothesis, but none of them are excluded either.

Preliminary

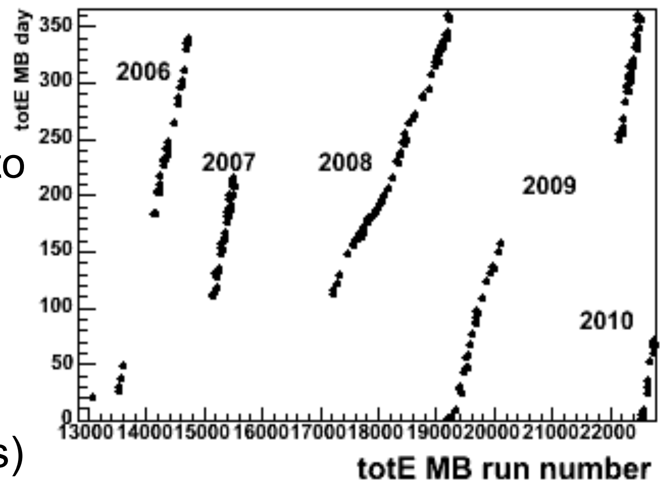
null hypothesis tests for neutrino mode						
	low energy		oscillation energy		total	
	solar	sidereal	solar	sidereal	solar	sidereal
# of events	544		420		964	
Pearson's χ^2:						
$N_{\mathrm{d.o.f}}$	107	107	83	82	191	191
χ^2	107.6	106.0	69.6	76.2	179.6	164.5
$P(\chi^2)$	0.47	0.51	0.85	0.66	0.71	0.92
Kolmogorov-Smirnov:						
$P(\mathrm{KS})$	0.42	0.13	0.81	0.64	0.64	0.14

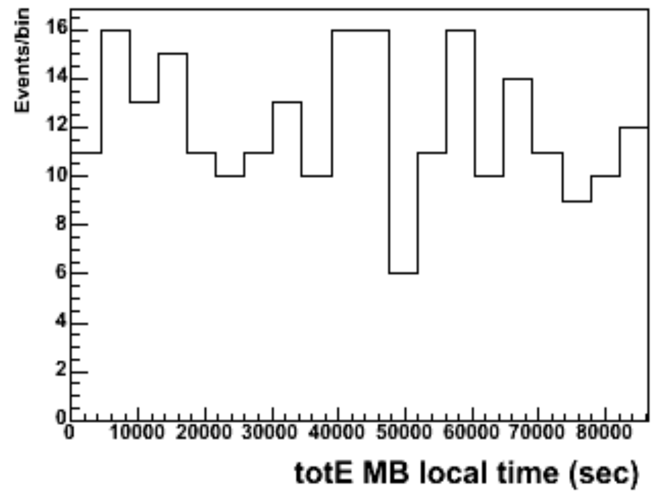
6. Lorentz violation with MiniBooNE anti-neutrino data

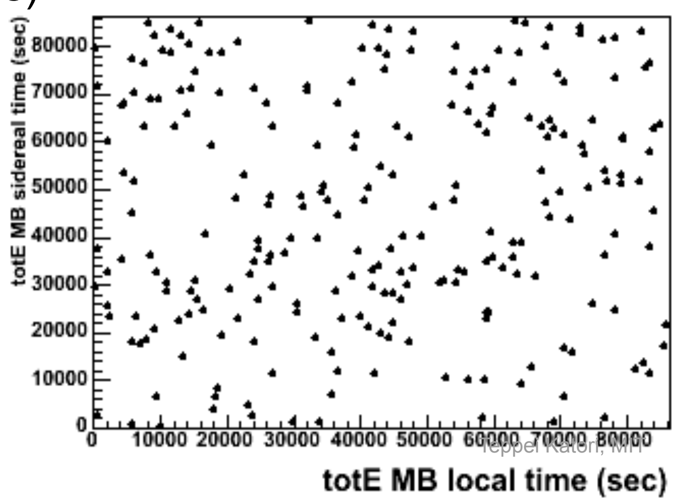
Time distribution of MiniBooNE antineutrino mode oscillation region

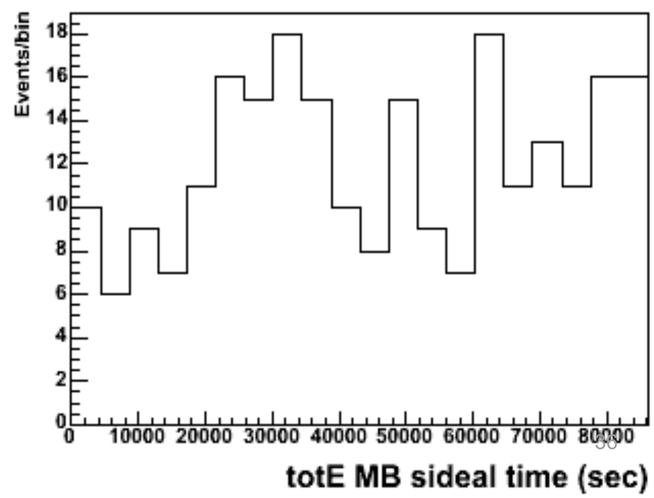
MiniBooNE data taking is reasonably uniform, so all day-night effect is likely to be washed out in sidereal time distribution.

solar local time 24h00m00s (86400s)
sidereal time 23h56m04s (86164s)









6. Lorentz violation with MiniBooNE anti-neutrino data

Null hypothesis test

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Non of tests shows any statistically significant results.

All data sets are compatible with flat hypothesis, but none of them are excluded either.

Preliminary

null hypothesis tests for anti-neutrino mode

	low energy		oscillation energy		total	
	solar	sidereal	solar	sidereal	solar	sidereal
# of events	119		122		241	
Pearson's χ^2:						
$N_{\mathrm{d.o.f}}$	21	22	23	23	47	46
χ^2	18.3	23.4	13.0	18.9	46.4	58.5
$P(\chi^2)$	0.63	0.38	0.95	0.71	0.50	0.10
Kolmogorov-Smirnov:						
$P(\mathrm{KS})$	0.62	0.15	0.79	0.39	0.69	0.08